

# Design and Implementation of the MARG Human Body Motion Tracking System

Xiaoping Yun, Eric R. Bachmann<sup>+</sup>, Andreas Kavousanos-Kavousanakis, Faruk Yildiz, Robert B. McGhee

Naval Postgraduate School, Monterey, CA 93943, USA

<sup>+</sup>Miami University, Oxford, OH 45056, USA

**Abstract**—Real-time tracking of human body motion has applications in tele-operation, synthetic reality and others. A motion tracking system based on use of the MARG sensors has been under development at Naval Postgraduate School and Miami University. The Magnetic, Angular Rate, and Gravity (MARG) sensor modules use a combination of three orthogonal magnetometers, three orthogonal angular rate sensors, and three orthogonal accelerometers to measure 3-D orientation of individual limb segments in order to determine posture. This paper presents the latest results of the MARG human body motion tracking system. The design and implementation of a Control Interface Unit (CIU), a real-time 3-D human avatar called “Andy,” and a concurrent client-server program are discussed. Experimental testing and evaluation of the overall MARG system is also presented. The system is able to track multiple human limbs in real time. The captured human motion data can be visualized over the Internet by multiple clients using the 3-D avatar.

**Keywords** - Human body motion tracking; MARG sensors; avatar; wireless communication.

## I. INTRODUCTION

Accurate real-time tracking of human body motion is important for many applications that involve human-machine interactions. One such application is in virtual training [1]. Real-time motion tracking makes it possible to create immersive virtual environments in which trainees will act and react as if the environments were real. Captured human motion data can also be used to control humanoid robots [1] [3]. Measurements of human body movements can be used to estimate physical and mental conditions of patients in clinical applications [4]. Motion tracking of human movements is widely used in sports training and production of animated movies.

There are a number of technologies for tracking human body motion, including mechanical trackers, active magnetic trackers, optical tracking systems, acoustic tracking systems, and inertial tracking systems [5][6][7]. Among the inertial tracking systems, Sakaguchi et al. [8] describes a gyroscope and accelerometer-based motion tracking system for tracking human arm motion. Lee and Ha [9] reports a study of human motion tracking using only accelerometers. There are broadly two kinds of image-based motion tracking methods. One method requires markers on the tracked human body, and other method does not use markers.

OPTOTRAK from Northern Digital Inc. is a typical example of a marker-based system [10]. Another is the motion tracking method developed for the CAVE system [11]. Marker-free methods are in general preferred because they are less cumbersome [12][13]. In most cases, multiple cameras are used to overcome occlusion problems and to construct 3-D motion data from 2-D images [14][15].

This paper presents a MARG sensor-based motion tracking system. The Magnetic, Angular Rate, and Gravity (MARG) sensor modules use a combination of magnetometers, angular rate sensors, and accelerometers to measure 3-D angular motion of rigid bodies. MARG sensors are self-contained, and do not require any artificially generated sources. They are constructed using MEMS sensors. As a result, they are small and are power-efficient. MARG sensor module design and implementation details were presented in [16]. A quaternion-based Kalman filter used to process MARG data was discussed in [17].

This paper presents other components of the MARG human motion tracking system, and experimental testing results of the overall system. These presented components include the Control Interface Unit (CIU), the 3-D human avatar, “Andy,” and a client-server protocol for transmitting MARG animation data. The CIU is designed to provide control signals to and multiplex measurement data from multiple MARG sensor modules. It packages measurement data from up to 16 MARG sensors for wireless transmission using the 802.11b wireless LAN standard. “Andy,” the human avatar is a cartoon-type avatar developed using X3D [18] and follows the H-Anim specification [19]. It is specialized to allow animation using orientation data expressed relative to an Earth fixed reference frame such as that provided by MARG sensor modules. The MARG human motion tracking system allows multiple clients to visualize the captured human motion over the Internet using the avatar Andy, supported by the client-server program.

## II. MARG SENSORS

MARG sensor modules are designed to provide data for measuring 3-DOF orientation in real time without singularities [17]. A more detailed description of the

design and implementation of the third generation prototype can be found in [16]. The dimensions of the MARG III are 28 x 30.5 x 17.3 mm. It weighs approximately 8.5 grams (0.3 oz). Power consumption is 144 mW (20 mA) when powered with 7.2 Volts. Sampling rate is 100 Hz. The MARG III is fabricated by McKinney Technology [20].

The MARG III contains three major sensing components. A pair of the two-axis (HMC1052) and one-axis (HMC1051Z) magnetic sensors are used for low frequency, three dimensional measurement of the direction of the local magnetic field vector. A pair of two-axis Analog Devices ADXL202E acceleration sensors is used for low frequency, three dimensional measurement of the gravity vector relative to the coordinate frame of the sensor module. A triad of orthogonally mounted NEC/TOKIN CG-L43 ceramic angular rate sensors are used for high frequency measurement of sensor module body rates. Two of the three sensing components of the MARG III (the magnetometers and the rate sensors) produce analog data. The Texas Instruments MSP-430F149 microcontroller is a fourth major component in the sensor module. It performs the analog-to-digital conversion of data and transmits digital data to the CIU. After collection and retransmission by the CIU, MARG sensor data is processed by a filter that takes advantage of the complementary characteristics of the installed sensor components [17].

### III. CONTROL INTERFACE UNIT (CIU)

#### A. Role of the Control Interface Unit

When completed, the MARG human motion tracking system will deploy 15 MARG sensors to track motion of 15 limb segments. There is a need to multiplex measurement data from all 15 MARG sensors and transmit them to a network-based computer for processing. For this and other purposes, the concept of the Control Interface Unit (CIU) was introduced. It is a component of the motion tracking system that is designed to be worn by the user at the waist or on the back. All 15 MARG sensors are connected to the CIU by a custom-made cable. Through this cable, the CIU delivers the power and the clock signal to each of the MARG sensors. The MARG sensors transmit measurement data to the CIU. The CIU then multiplexes the measurement data from multiple MARG sensors, and wirelessly transmits the data to a networked PC (server) for processing. The wireless transmission is achieved using the IEEE 802.11b standard.

The MARG sensor communicates with the CIU through a Universal Synchronous Asynchronous Receiver Transmitter (USART) operating in the Synchronous Peripheral Interface (SPI) mode. In this

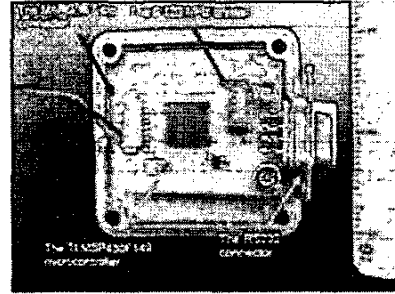


Figure 1. The One-Channel Control Interface Unit (One-Channel-CIU).

configuration, the MARG sensor operates as a slave device whereas the CIU is the master device. The clock signal needed for synchronizing the data transmission is delivered to the MARG sensor by the CIU.

#### B. The One-channel CIU

The CIU was designed and implemented in stages. A one-channel CIU was designed and implemented first. It connects to one MARG sensor, and delivers the output data by a standard RS232 port. An 802.11b wireless serial adaptor named WiSER2400.IP from OTC Wireless Inc. [21] was utilized for wireless transmission of the output data to the networked PC. A picture of the one-channel CIU is shown in Figure 1. The main component of the one-channel CIU is a TI MSP430F149 microcontroller identical to the one onboard the MARG III sensor.

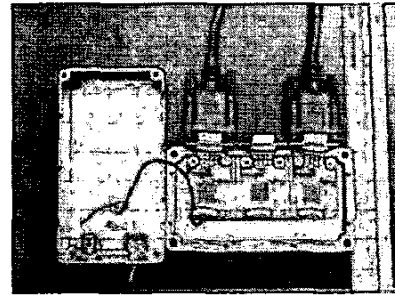


Figure 2. The Three-channel Control Interface Unit (Three-channel CIU).

#### C. The Three-channel CIU

After the one-channel CIU was designed, implemented, and successfully tested, a three-channel CIU was built. The purpose of the three-channel CIU was to test motion tracking of multiple limb segments with multiple MARG sensors, and to test the operation of

the human avatar Andy and the client-server program (discussed later). The three-channel CIU is shown in Figure 2. It is constructed from three one-channel CIUs in a parallel configuration.

#### D. The Sixteen-channel CIU

The MARG motion tracking system is designed to simultaneously track 15 limb segments. For this purpose, a sixteen-channel CIU was designed. Sixteen rather than fifteen was chosen because input/output number of multiplexers usually is in power of two. This CIU is to multiplex all measurement data from 16 MARG sensors, packages them in a proper format, and transmit them using a single wireless communication channel. The selected multiplex method was to use a XILINX® Spartan™-II XC2S100 Field Programmable Gate Array (FPGA) [22]. The prototype board of the sixteen-channel CIU is shown in Figure 3.

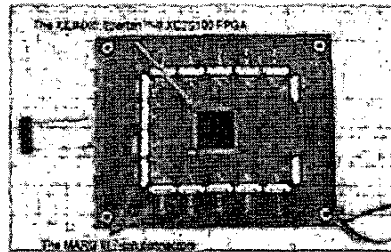


Figure 3. Top View of the Sixteen-channel Control Interface Unit (Sixteen-channel CIU).

TABLE I. THE SIXTEEN-CHANNEL CIU OUTPUT FORMAT

| Number of Bytes  | Content                                    |
|--|--|
| 2  | Communication Synchronization              |
| 2  | MARG III "Alive" Identification Bits       |
| 2  | Payload "Health" Status                    |
| 1  | Timing                                     |
| 1  | Sample Number                              |
| (13.5 + 0.5) x 16 MARG III sensors<br>(Total of 224 bytes) | Payload and MARG III Identification Number |
| <b>Total: 232 Bytes</b>                                    |  |

The data format used by the CIU shown in Table 1 consists of 232-byte words, which include the data from all sixteen MARG III sensors and the necessary communication overhead. In the event that one or more MARG III sensors are not connected or that they transmit incorrect data, the FPGA replaces the respective bits with zeros in order to keep a constant transmission rate.

The data for each of the sixteen MARG III sensors consists of the measurements from the three magnetic (Mx, My, Mz), the three angular rate (Rx, Ry, Rz), and the three acceleration sensors (Ax, Ay, Az) onboard the MARG III sensor (nine channels for each sensor). Each channel (transmitted in the order of Rx, Ry, Rz, Ax, Ay,

Az, Mx, My, Mz) occupies one and a half byte, giving a total of 13.5 bytes of data for each MARG III sensor. An identification number of a half a byte is added to associate the data received with the corresponding MARG III sensor. This ID number leads to a total payload of 14 bytes for each MARG III sensor.

An 802.11b wireless LAN OEM module Airborne from DPAC Technologies [23] was used for wireless transmission. The Airborne unit is interfaced to the TI microprocessor onboard the CIU using UART. The data transmission rate is 232 kbps.

#### IV. HUMAN AVATAR ANDY

Avatar Andy was developed to allow networked viewing of human body motion using a web browser. It is a cartoon-type avatar created using the Extended 3D (X3D) language [18]. It is a modification of the low-resolution avatar named AndyLow, developed by Seamless Solutions, Inc. [24]. AndyLow was originally implemented using the Virtual Reality Modeling Language (VRML) and follows the H-Anim specification [19]. It was converted to X3D, an extended version of VRML [25]. Modification of AndyLow was required due to the characteristics of orientation estimates produced from MARG data [25].

The geometries of all limb segments in the AndyLow avatar are described relative to a single unique reference frame, located at the center point between the feet. Limb segments are arranged in a hierarchy radiating from this reference point with the segments that are closer to the reference being termed "inboard" of those that are further away. Joint rotations for each limb segment must be set using an orientation that is relative to the reference frames of each of the more inboard joints. Limb segment orientation estimates derived from MARG sensor data are given relative to an Earth fixed reference frame. This requires that each limb segment be oriented independently of all other segments. For this reason, AndyLow was incompatible with the system described here. To overcome this drawback, each segment's geometry was redefined using its own local reference position with only a connection point to the parent or next most inboard segment.

The H-Anim specification [19] defines several levels of articulation. Highly detailed levels allow for the individual animation of minor limb segments such as finger joints. Coarser levels only allow individual animation of major limb segments such as the upper leg or lower arm. Level one articulation (LOA-1) is preferred for AndyLow. This level offers 18 joints arranged in a hierarchical human skeleton structure. The MARG system was designed to track up to 15 individual limb segments. Avatar Andy fixes the *sacroiliac*, *l\_midtarsal* and *r\_midtarsal* joints in order to reduce the total number limb segments to 15. Figure 4 shows the skeleton

structure of the avatar Andy with numbering used to represent the joints. Figure 5 shows Andy in a standing position.

|                              |      |
|------------------------------|------|
| HumanoidRoot : sacrum/pelvis | [0]  |
| l_hip : l_thigh              | [1]  |
| l_knee : l_calf              | [2]  |
| l_ankle : l_hindfoot         | [3]  |
| r_hip : r_thigh              | [4]  |
| r_knee : r_calf              | [5]  |
| r_ankle : r_hindfoot         | [6]  |
| v15 : 15                     | [7]  |
| skullbase : skull            | [8]  |
| l_shoulder : l_upperarm      | [9]  |
| l_elbow : l_forearm          | [10] |
| l_wrist : l_hand             | [11] |
| r_shoulder : r_upperarm      | [12] |
| r_elbow : r_forearm          | [13] |
| r_wrist : r_hand             | [14] |

Figure 4. Hierarchical Skeleton Structure of the Avatar Andy.

Real-time orientation data is supplied to avatar Andy through a Java Script node. The node contains a TCP socket for handling control information and commands. Orientation data is received via a separate UDP socket. The avatar is thus capable of controlling all its 15 joints in networked virtual environments (NVEs).

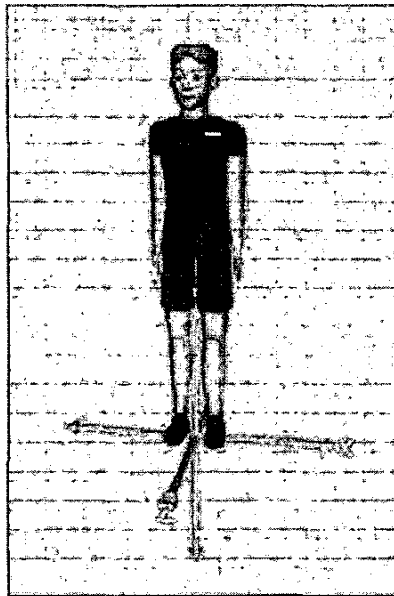


Figure 5. Avatar Andy.

## V. CONCURRENT CLIENT-SERVER PROTOCOL

Networking capability was added to the MARG system in order to produce a flexible system with real-time data streaming. Therefore, a concurrent client-server

program is developed to provide a network interface to the system. The concurrent client-server program receives MARG sensor data through a UDP socket and delivers the data to the clients on the wide area network (WAN) simultaneously. Delivering the same motion data to multiple clients simultaneously is implemented by a method called Multicasting Using TCP and UDP Protocol (MUTUP) [25].

Multicasting is the most efficient way of transmitting information among a large number of group members spread out over different networks. Reduced network bandwidth use is the major advantage of using multicasting protocols. Unfortunately, most routers on the Internet are not configured for multicasting. A technique called tunneling is used to overcome this problem. Tunneling is a software solution that runs on the end point routers/computers and allows multicast packets to traverse the network by putting them into unicast packets. MUTUP overcomes the tunneling problem using shared memory in the server and a unicast TCP and UDP messages between the server and each client. The major disadvantage of MUTUP is a limitation on the number of clients that can be handled by the server at any time. This limitation is caused by an increase in load on the CPU and additional memory consumption for each client. Low performance or out-of-memory problems may occur if the server must handle too many clients. MUTUP also uses greater network bandwidth than multicasting because separate update messages must be sent to each client. Since a relatively small number of clients are expected in the MARG project, MUTUP was chosen as an alternative method to the multicasting protocol despite its drawbacks.

MUTUP uses shared memory in the server program for storing the latest motion data. Clients request TCP connections from the server. The server accepts the requests and creates a separate thread for handling each of the connections. The TCP connection is used for general-purpose communication. The TCP protocol is not appropriate for data streaming due to increased latency and overhead. Therefore, a second connection based on UDP sockets is established between the client and the server. The server program asks the client to create a UDP socket and send the IP address and the UDP port number of this socket back to the server. The server adds the IP address and the UDP port number of the client as a destination for the packets sent by the server program. To provide the same motion data for all connected clients simultaneously, a shared memory array that always stores the latest update is created on the server program. An updater thread updates this array. All client handler threads access this array at any time they want. A diagram of MUTUP is provided in Figure 6.

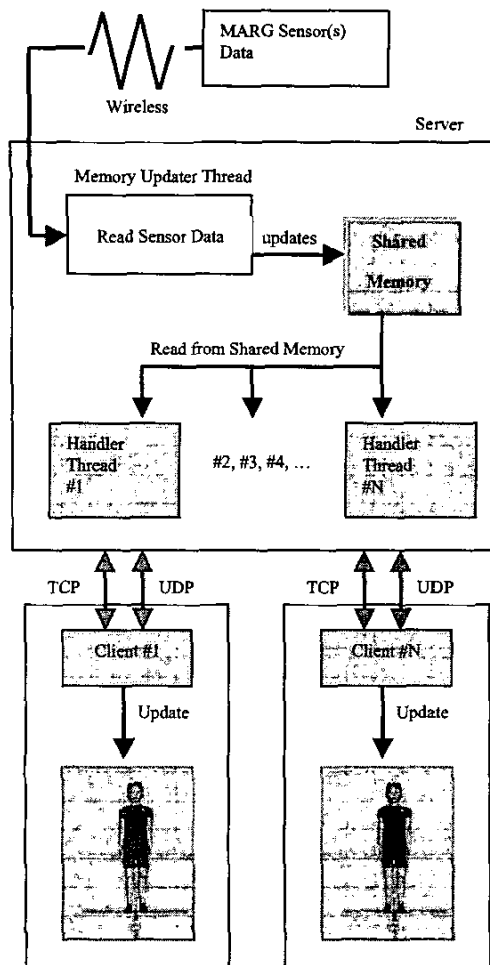


Figure 6. Concurrent Client Server Communication.

## VI. TESTING AND EVALUATION

The performance of the individual MARG sensors was tested first. Each MARG sensor produces nine components of raw measurement data at the rate of 100 Hz. The raw measurement data are processed by the filter algorithm [17] to produce a quaternion representation of orientation. For plotting purposes, quaternions are converted to Euler angles (roll  $\phi$ , pitch  $\theta$  and yaw  $\psi$ ). Figure 7 shows the output of the MARG sensor as it performs a 720° rotation (roll  $\phi$ ) about its longitudinal axis. It is seen that the sensor starts from a zero roll. When the motion starts, the sensor responds with a linear rotation toward negative 180°. The plot displays angles within the range of negative 180° and positive 180°. Therefore, a sudden transition from negative 180° to positive 180° appears. In reality, the

sensor continues to rotate with a constant angular rate until it reaches a full 720° rotation and then stops. A slight pitch deviation and an even smaller yaw deviation are also observed.

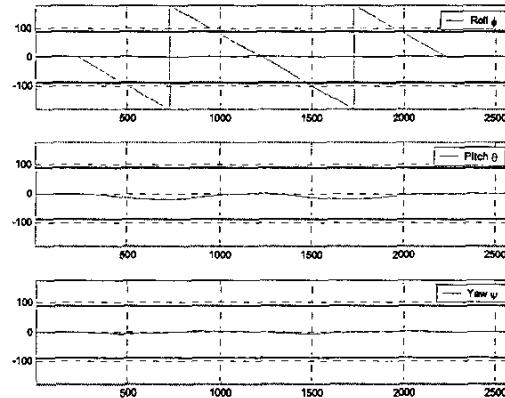


Figure 7. Response of MARG Sensor to 720° Roll Motion.

The real-time performance of the overall tracking system was evaluated in connection with the human avatar Andy. Two MARG sensors were attached to an arm of a user, and connected to the three-channel CIU. The CIU then wirelessly transmitted the sensor data to a network-based server computer. The sensor data were filtered, and the resulting orientation quaternions were transformed into axis-angle pairs. This transformation was necessary since the avatar was created using the X3D language, which has been standardized to use axis-angle pairs to represent rotations.

Testing results with the full-body avatar were very successful. With the use of two MARG III sensors, the avatar followed the motion of the human right arm exactly. Figure 8 and Figure 9 show two snapshots of the testing scene. The user moves his arm, and the motion is followed in real time by the avatar.

## VII. CONCLUSION

The paper presents the system components of a body motion tracking system based on MARG sensor modules and testing and evaluation results for a prototype three-sensor system. The components presented include a Control Interface Unit, a human avatar, and a Client/Server protocol for transmitting animation data. The CIU packages data from up to 16 MARG sensors for wireless transmission. The Client/Server program receives MARG sensor data and delivers that data to multiple clients simultaneously. The avatar allows networked viewing of animations produced using MARG data in real time. Tests of a prototype three sensor system indicate that these components provide the necessary infrastructure to support a 16 sensor system for full body tracking.

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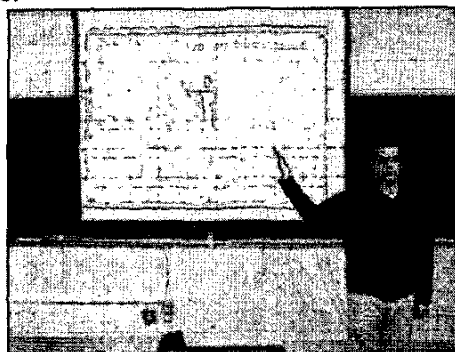


Figure 8. Avatar Andy and the User in Real-Time Testing.

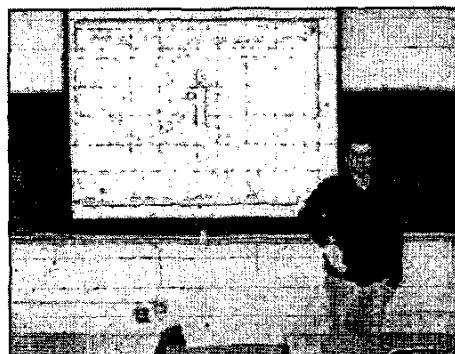


Figure 9. Another View of Avatar Andy and the User in Real-Time Testing.

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